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# Assessing Water Sustainability Related to Hospitals Using System Dynamics Modeling

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## Abstract

Water is a critical but limited resource. As the population increases, the demand for this resource is growing. However, water needs to be sustained for current as well as future generations. Sustainability considers the balance between social, economic, and environmental factors. Hospitals are one of the major stakeholders within healthcare systems and one of the top users of water resources. This paper discusses a systems thinking approach to evaluate water sustainability related to hospitals and considers how different factors related to hospitals and water sustainability associate to each other. A system dynamics simulator is presented that models the behavior of different factors related to hospitals and water sustainability. The model can help decision makers make more informed decisions related to the factors that have an impact on water sustainability related to hospitals such as water reuse and water reduction. Information about the simulator is presented along with initial results using actual hospital data.

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**Keywords:** Systems thinking; system dynamics; simulation; sustainability; water sustainability; hospital; healthcare

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## 1. Introduction

Sustainability is defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [1]. It considers both the needs of the present and future generations [2].

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In general, sustainability incorporates three components: social, economic, and environmental [1]. These three components are known as three pillars of sustainability. They are interdependent and mutually reinforcing [3].

Water is related to all the three pillars of sustainability. One of the most critical challenges the world is facing is to ensure everyone has access to an adequate and quality supply of water. Therefore, water needs to be sustained for current and future generations.

Hospitals are one of the major stakeholders within healthcare systems and have a major role in healthcare. They also have multiple stakeholders that can include patients, staff, visitors, and vendors. Hospitals are one of the top ten water users in their communities [4].

This paper discusses a systems thinking approach applied to water sustainability related to hospitals. A causal model is presented that provides a graphical illustration of the factors and factor relationships related to water sustainability and hospitals. A system dynamics simulator is developed that includes a set of the validated causal model factors and factor relationships related to hospitals and water sustainability. The simulator models the behavior of different factors related to water sustainability. A validation of the simulator architecture model is also performed. Information about the simulator is presented along with initial results.

## 2. Causal Model for Water Sustainability Related to Hospitals

Systems engineering can be applied to large and complex systems and focuses on the system as a whole. Hospitals are large complex systems. Systems thinking is a systems engineering approach that can help to understand and address challenges in different systems. A systems thinking perspective offers a holistic view of a system.

System dynamics (a systems thinking method) can help in understanding complicated relationships between key factors. This method was developed by Forrester [5]. System dynamics supports understanding the dynamic feedback behavior in complex systems. System dynamics was applied to visualize and explore structure and behavior of factors and factor relationships related to water sustainability in hospitals.

In order to better understand the factors and factor relationships that relate to water sustainability in hospitals, a causal model was developed. Causal models are used as part of the system dynamics approach. These models capture major feedback mechanisms within this system.

Faezipour and Ferreira [6] performed a detailed literature review and analysis of healthcare factors and developed healthcare sustainability causal models. Additional study was performed specific to water sustainability related to hospitals in Faezipour and Ferreira [7] that resulted in the identification of a set of factors and relationships that are represented in a causal model related to water sustainability and hospitals. The causal model covers factors related to water use within and outside the scope of hospitals. Presenting the entire causal model is not feasible within the limits of this paper. Therefore, only a subset of the causal model is presented in Fig 1.

### 2.1. Causal Model Feedback Loops

Factors in the causal model relate to the three pillars of sustainability. The causal model includes a number of feedback loops. For the purpose of understanding the model, a feedback loop related to each sustainability pillar is presented. The feedback loop in Fig 2 (a) represents factors related to the social pillar. This loop includes level of demand for services and resources for patients, level of accessibility to services and resources, and quantity of patient complaints. Another feedback loop (Fig 2 (b)) includes actual volume of water needed, water footprint, price of water, water cost in hospital, cost of services and resources, level of accessibility to services and resources, quantity of patient complaints, and level of demand for services and resources for patients. This feedback loop illustrates factors related to the economic pillar. The feedback loop shown in Fig 2 (c) includes factors related to the environmental sustainability pillar and includes quantity of patients, amount of hospital waste products, level of external fresh water quality, and level of overall population wellbeing.

### 2.2. Feedback Loop Factor Definitions

In the causal model feedback loops, quantity of patients defines the total number of patients entering the hospitals. Level of demand for services and resources for patients represents the patients need for hospital resources and services including medication, healthcare facilities, and equipment. Level of accessibility to services and

resources provides a measure to ensure all the patients have equal access to the services and resources offered in the hospital. Quantity of patient complaints defines the total number of patients that are not satisfied with the services and resources offered at the hospital and will not return to receive services and resources. Quantity of patient complaints and level of accessibility to services and resources are both important factors in the model. These factors are related to patient satisfaction which is one of the key factors related to healthcare sustainability [8].

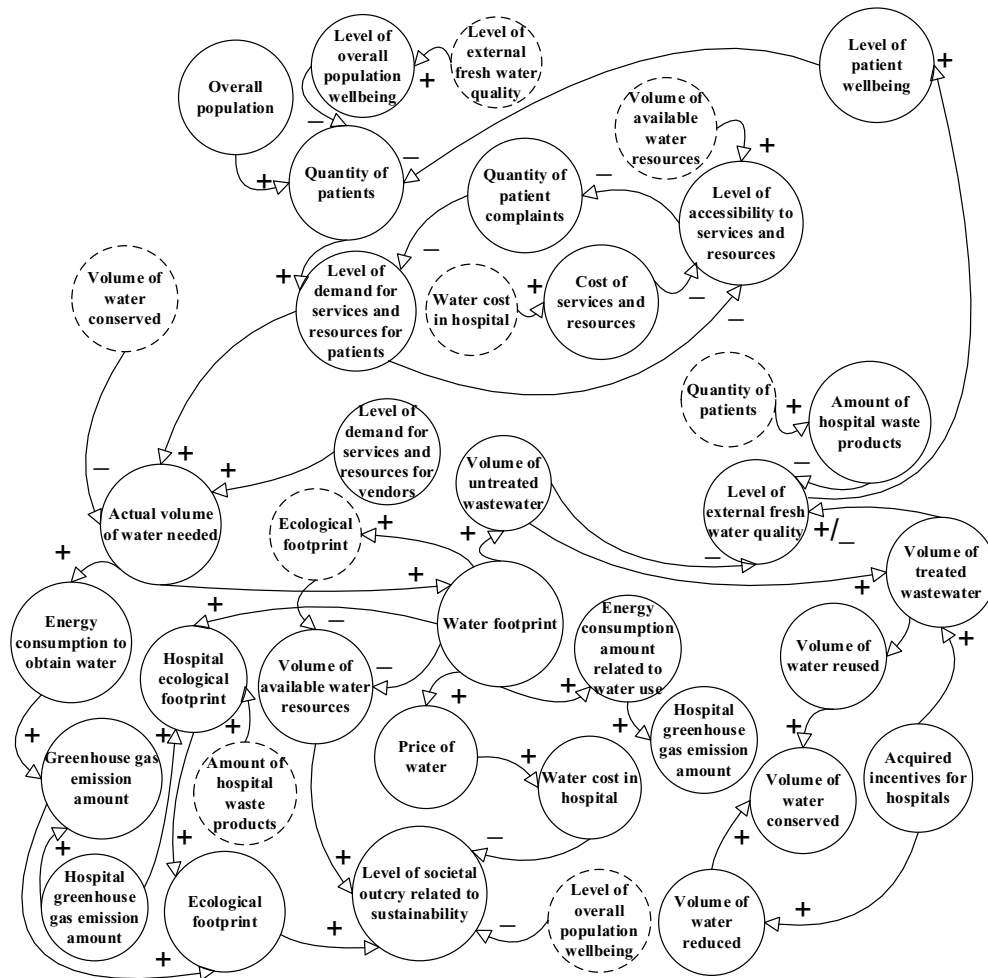


Fig. 1. Causal model for water sustainability related to hospitals (subset)

Cost of services and resources defines the total cost of services and resources offered to patients in hospitals during their stay. This includes cost of trained staff and resources including medication, equipment, and hospital fees and bills. Price of water represents the actual value of water that is determined by the water usage. Water cost in hospital is the total cost of water used in the hospital. Actual volume of water needed defines the actual amount of water that is needed for use in the hospital. Water footprint represents the total amount of water that is used by the hospital. Amount of hospital waste products is the waste that is produced by patients, staff, visitors, and vendors such as waste produced from hospital food or supplies. Level of external fresh water quality represents the quality level of the external fresh water resources. Level of overall population wellbeing represents level of overall population's health.

In order to help understand feedback loops, the next few sentences will discuss the feedback loop related to the economic pillar. When patients have more access to the services and resources, they will be more satisfied and will have fewer complaints. This means as the level of accessibility to services and resources increases, the quantity of patient complaint decreases. When patient complaint increases, they will be less likely to have demand for services and resources therefore the level of demand for services and resources for patients decreases. As the level of demand for services and resources for patients including water increases the actual volume of water needed for water increases. The increase in need for water increases the water use (water footprint). As the water footprint increases, price of water increases and this will also increase the cost of water in hospital. The cost of water will also increase the cost of services and resources related to patients in hospitals. As the cost of services and resources increases, the accessibility to services and resources is expected to decrease and patients become less satisfied with the services.

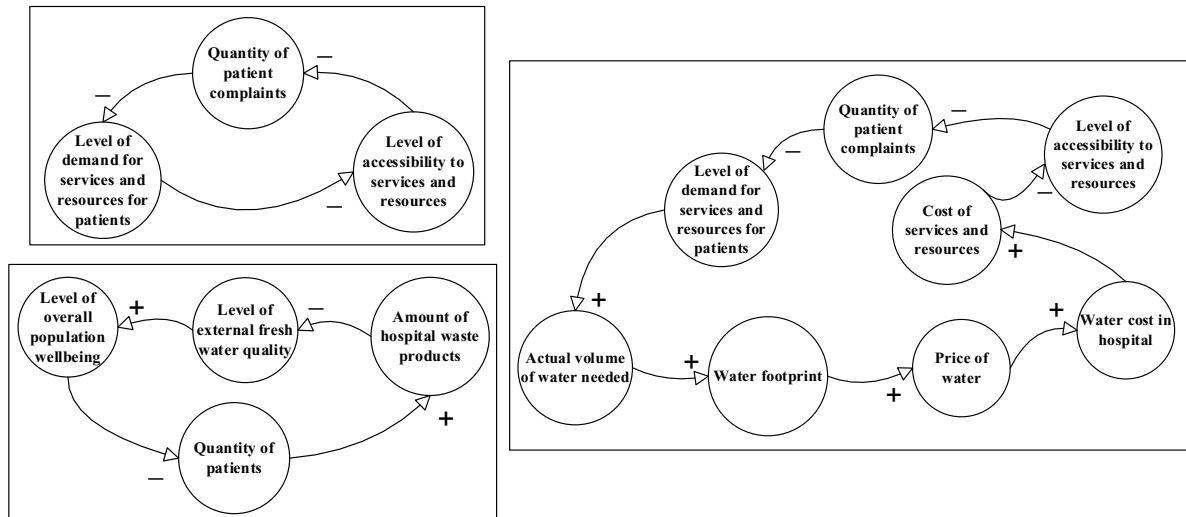


Fig. 2. (a) Feedback loop related to the social pillar (top left); (b) Feedback loop related to the economic pillar (right); (c) Feedback loop related to the environmental pillar (bottom left)

The causal model was validated with the help of hospital personnel in the Dallas Fort Worth (DFW) metroplex and is discussed in Faezipour and Ferreira [7]. The purpose of the causal model validation is to ensure the factors and factor relationships in the model are a reasonable representation of reality. The validated causal model is used to develop the water sustainability simulator related to hospitals.

### 3. Water Sustainability Simulator Related to Hospitals

A water sustainability simulator related to hospitals can help users to explore risks and evaluate the dynamic consequences of various decisions without having to interrupt or affect the existing hospital water system. The simulator models the factors and factor relationships that relate to water sustainability and the three pillars of sustainability (social, economic, and environmental). The system dynamics simulator includes a set of the validated causal model factors and factor relationships.

The simulator architecture was developed using the iThink simulation software. A subset of the simulator architecture is presented in Fig 3. This subset is related to the environmental pillar.

#### 3.1. Simulator Architecture Validation

The simulator validation is performed in two stages. The first stage is the validation of the simulator architecture and the second stage is the validation of the populated version of the simulator. This section of the paper discusses the simulator architecture validation. The purpose of the validation process is to ensure that the architecture of the simulator is valid and is a reasonable representation of reality.

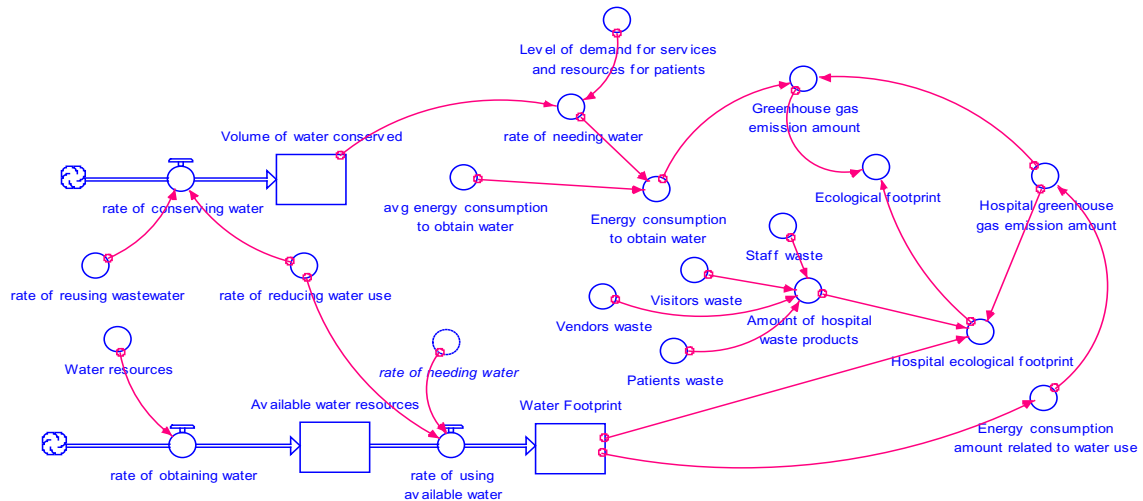


Fig. 3. Water sustainability simulator related to hospitals (subset)

The simulator architecture validation process was performed using guidelines and model tests from the Richardson and Pugh [9] framework that builds confidence in the model. Since, at this stage, there was no data included in the simulator architecture, only one test was performed from the Richardson and Pugh framework. The criterion checked is identified as “face validity”. Face validity checks the model’s structure to verify it looks like the real system and represents the essential characteristics of the actual system.

A validation package was prepared and presented to a set of subject matter experts in DFW metroplex hospitals. This package included the causal model and the simulator architecture along with tables that described the factors and variables. Questions were asked to ensure the structure of the simulator architecture represented the real system. For each variable, the validators were asked if the variable was valid, if the variable definition was reasonable, and if the unit of measure was reasonable. Validators were asked to verify the relationships were reasonable and identify if there were any missing or incorrect variables or relationships. Validators were also asked to provide additional comments. The simulator was updated and modified based on recommended changes and feedback from validators.

### 3.2. Simulator Data Collection

After the simulator architecture was validated, a data collection package was developed to elicit information needed to populate the simulator. The data package was provided and presented to hospitals in the DFW metroplex. The data collection package included a set of questions about the variables in the simulator that the hospital representatives would be able to fill in. For data that was not available from hospitals, other resources and databases were used to fill in the information. In order to obtain some initial results, the variables in the simulator were populated with data collected from the data collection package for one hospital in the DFW metroplex. These variables are either direct inputs (e.g., overall population) or a calculated amount based on other variables.

## 4. Initial Simulator Results

A simulator enables decision makers to see and understand the impacts of different decisions. Various scenarios may occur within the current water sustainability system. The evaluation of results generated from these scenarios can allow the assessment of different policies associated to water sustainability related to hospitals. Some simulator outputs that are important for hospitals include level of overall population wellbeing, level of patient wellbeing, cost of services and resources, hospital ecological footprint, and level of external fresh water quality.

One of the input variables in the simulator is the volume of water reduced by the hospital. Reducing the water use contributes to water conservation. Two scenarios were examined in the simulator to evaluate the impact on the hospital ecological footprint. Hospital ecological footprint represents the amount of land and water area required for nature to regenerate the resources used by the hospital. Hospitals can implement different policies to decrease their ecological footprint. This decrease affects the overall ecological footprint. As the hospital ecological footprint

decreases, the overall ecological footprint will decrease. As a result, the level of societal outcry related to sustainability will decrease.

One scenario is a baseline case and is performing no water reduction. The other scenario reduces water use by 15%. For the water reduction scenario, the hospital ecological footprint will reduce by 0.02 global hectares (gha) in comparison to the baseline case. A global hectare is equivalent to one hectare of land or water with average productivity ability [10]. At end of the simulation run, with the no water reduction policy, the hospital ecological footprint is 0.14939 gha. The hospital ecological footprint is 0.13257 gha for the end of the same run with the water reduction policy. Given these results, it is expected that when hospitals use water reduction methods, there will be a reduction in the ecological footprint.

The model allows the decision maker to consider various levels of water reduction and water recycling. Hospitals can use the simulator to evaluate different water conservation policies to understand the impact of their decisions on simulator outputs. This is a work in progress and once additional results are processed they will be published in upcoming papers.

## 5. Summary and Future Work

Water sustainability is an important concern for everyone. There is a need for research and methods for evaluating water sustainability. A systems thinking approach was applied to understand how various factors related to hospitals and water sustainability interrelate. Certain aspects of the models developed can be applied to other types of organizations. However, there are factors in the model that are hospital specific and would not be applicable to other types of organizations and systems.

System dynamics, an approach within systems thinking, was utilized to visualize and explore the structure and behavior of factors and factor relationships related to water sustainability in hospitals. A causal model was developed that presents a graphical illustration of the factor and factor relationships. The validated set of causal model factors and factor relationships were inputs to the development of the water sustainability system dynamics simulator related to hospitals. The simulator models the behavior of different factors related to hospitals and water sustainability and helps decision makers comprehend the impacts of their decisions. Individuals who influence healthcare systems and hospitals can use such a simulator to make more informed decisions, leading to a more proactive paradigm. The simulator factors are general and can be applied to various types of hospitals. However, the simulator inputs and data used in the equations would be calibrated to the hospital of interest.

The simulator architecture was validated to ensure that the model represents the essential characteristics of the actual system. Based on inputs received from simulator validation results, the simulator was updated and modified. Data was collected from a hospital and some initial results were presented.

The initial set of simulator runs presented in this paper were performed using results from one hospital. Collecting data from other hospitals in the DFW metroplex is underway. Additional hospital data will be entered in the model and results will be evaluated. The next step in the research includes verification and validation (V&V) exercises based on the populated version of the model.

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